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Estimating the redshift of PKS 0447−439 through its GeV–TeV emission

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ABSTRACT

Context. Blazars are radio-loud active galactic nuclei (AGN) with a jet pointing at small angles towards the observer. The overall emitted spectrum is typically non-thermal, and in some cases the emission and/or absorption lines are so faint as to prevent the determination of the redshift based on optical spectroscopy methods. PKS 0447−439 is a bright blazar recently detected at very high energy. The redshift of the source is still disputed: a recent spectral analysis reports only a lower limit of $z > 1.246$, which contradicts the previous measure of $z = 0.205$ reported in the literature.
Aims. We aim to give a redshift estimate of the blazar PKS 0447−439 based on combined GeV (*Fermi*/LAT) and TeV (H.E.S.S.) observations.
Methods. Taking into account the absorption of TeV photons by the interaction with the extragalactic background light (EBL), we applied the method we developed in a previous work to derive the redshift of PKS 0447−439. Moreover, we compiled the overall spectral energy distribution (SED) using optical-UV, soft X–ray, and γ-ray data, nearly simultaneous to the H.E.S.S. observations at TeV energies. Finally we modelled the spectral energy distribution (SED) within the framework of a homogeneous, leptonic synchrotron self-Compton (SSC) model.
Results. Using the recent TeV spectrum measured by H.E.S.S. we obtain for PKS 0447−439 a redshift of $z_{rec} = 0.20 \pm 0.05$, which is our estimate on the source distance. This value agrees very well with the value reported in the literature and confirms that our method can be successfully used to constrain blazars distances. Assuming this distance, the SED can be well fitted with the above mentioned model. The physical parameters that we find suggest a strongly matter-dominated jet.
Conclusions. Our analysis confirms that the redshift of PKS 0447−439 is likely 0.2, and supports the result present in the literature.

Key words. BL Lacertae objects: individual: PKS 0447−439 - Galaxies: distances and redshifts - Gamma rays: galaxies

1. Introduction

The number of known AGN whose emission extends up to the very high energy (VHE; E > 100 GeV) γ–ray band has more than doubled in the last couple of years. Nowadays, the TeV sources catalogue counts 44 AGN[1], located both in the northern and in the southern hemisphere. This achievement has been made possible thanks to the good performances of the last generation of imaging atmospheric Cherenkov telescopes (IACT), namely MAGIC, H.E.S.S. and VERITAS. A key ingredient for the detection of new sources has been the cooperation of these telescopes with satellite experiments, especially those operating at optical, X–ray and soft γ–ray frequencies.

The great majority of AGN detected at VHE belongs to the class of blazars. In these sources, the emission is produced in relativistic jets that point towards the observer.

PKS 0447−439 is a blazar located at RA(J2000) = $04^h49^m24.^s88$, Dec.(J2000) = $-43°50'09.''7$. It was discovered in 1981 at radio wavelenghts by the Molonglo Telescope (Large et al., 1981) and detected by the PMN radio Survey in 1993 (Gregory et al., 1994).

The source was subsequently detected in the UV with EUVE (Lampton et al., 1997) and X–rays with ROSAT (White et al., 1994). Some confusion arose in the determination of the optical counterpart because at first a near–UV bright spectrum with prominent emission lines in the optical was related to PKS0447-439 (Craig et al., 1997). The source was therefore classified as a Type I Seyfert at $z = 0.107$. Instead Perlman et al. (1998) reported a featureless optical continuum typical of a BL Lac object.

We investigated this classification discrepancy, also inspecting some archival *Swift*/UVOT exposures of the field. We understood that the association of the Seyfert spectrum with this source is probably due to some databasing mistake, because the PKS 0447−439 coordinates reported in Craig et al. (1997) are incorrect, and point to a region that is source–free both in their optical finding chart and in our UVOT images.

The redshift of PKS 0447−439 was measured by Perlman et al. (1998), who reported a value of $z \sim 0.205$ based on few weak absorption features in the optical spectrum that were interpreted as the *Ca*H,K doublet. Another study performed by Landt & Bignall (2008) provided only a lower limit of 0.176, based on the non–detection of the host galaxy, which is assumed to be a giant elliptical of inferred luminosity (Piranomonte et al., 2007). Recently, a different lower limit z > 1.246 was obtained (Landt, 2012) based on the analysis of absorption lines in the optical spectrum. This new value is well above the measurement reported by Perlman et al. (1998).

[1] See TeVCat (http://tevcat.uchicago.edu/) and R. Wagner (http://www.mpp.mpg.de/~rwagner/sources/) pages.

The Large Area Telescope (LAT) instrument on board *Fermi* identified the source as one of the brightest of the southern hemisphere in the 100 MeV–300 GeV energy range (Abdo et al., 2009). Dedicated studies on the weekly light curve above 300 MeV revealed that the source is variable in this energy range (Abdo et al., 2010a). Inspired by the *Fermi*/LAT observations, the H.E.S.S. IACT observatory performed a dense observation campaign between November 2009 and January 2010. This led to the detection of a VHE signal, statistically significant above the 13 σ level and positionally consistent with PKS 0447−439, as preliminarily reported in Zech et al. (2011).

In this Paper, we derive an independent estimate of the distance to PKS 0447−439 using combined GeV and TeV spectral information, following the method we proposed in Prandini et al. (2010). Our goal is to provide a new measurement of the source's redshift, which is still uncertain, as discussed above. In the next section we briefly outline the method and present the result, which basically confirms the estimate of $z \sim 0.2$ given by Perlman et al. (1998). Then, we build a quasi-simultaneous SED, which is fitted with a homogeneous, leptonic SSC model. This allows the determination of the main physical parameters governing the jet physics.

2. Inferring the distance of TeV emitting blazars

The VHE spectrum of blazars suffers from the absorption arising from the interaction with the extragalactic background light (EBL) (Hauser & Dwek, 2001). This absorption, caused by electron-positron pair production (Nikishov, 1962), induces a partial/total deformation of the VHE part of the spectrum that is strongly redshift-dependent. In general, for nearby sources that are located at redshift below 0.1, it affects the spectral points above some TeV. At higher redshifts, between 0.1 to 0.5, it affects the spectrum already at some hundred of GeV, while above 0.5 it becomes effective already above some GeV. Therefore, given an intrinsic VHE spectrum, the observed one depends on the distance of the emitter. In other words, the optical depth associated to the absorption process depends on the distance covered by the energetic photon and on its energy. Unfortunately, owing to strong foreground emissions that are difficult to suppress, there are no solid measurements of EBL. Upper and lower limits are provided by indirect techniques such as galaxy counts, which provide solid lower limits. In addition to these measurements, many models of the EBL energy density and evolution have been proposed in the last years (Stecker et al., 2006; Franceschini et al., 2008; Kneiske & Dole, 2010; Domínguez et al., 2011). In this work we adopt the model presented in Franceschini et al. (2008).

To estimate the distance to PKS 0447−439, we applied the method that we proposed in Prandini et al. (2010) and updated in Prandini et al. (2011). This method is based on the comparison between the high energy (HE; $0.1 < E < 100$ GeV) γ–ray spectrum measured by *Fermi*/LAT and that measured at VHE by the last generation of imaging atmospheric Cherenkov telescopes (MAGIC, H.E.S.S. and VERITAS).

We refer the reader to the original paper (Prandini et al., 2010) for the full description of the method. Briefly, to infer the distance of an HE and VHE gamma-ray emitting blazar, we calculate the redshift, z^*, at which the power law slope fitting the VHE spectrum corrected for the EBL absorption equals the slope measured by *Fermi*/LAT at lower energies. As empirically demonstrated in the paper using a set of known redshift sources, this value is related to the true redshift of the source by a simple linear relation. Therefore, once one has obtained z^*, it is possible to give an estimate on the source distance, z_{rec}, by using the inverse formula:

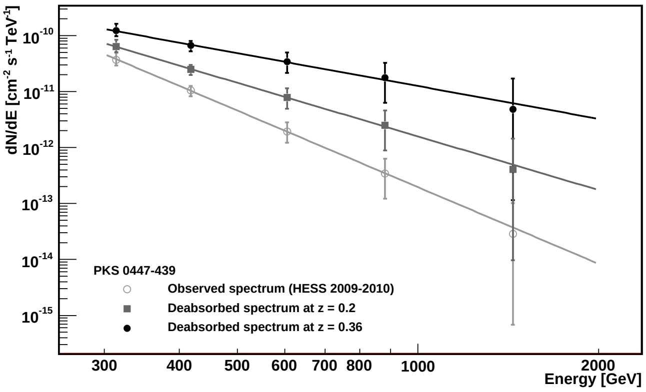

Fig. 1. Observed (light grey, open circles) and deabsorbed VHE spectra of PKS 0447−439, as reported in Zech et al. (2011). Deabsorption is applied assuming the Franceschini et al. (2008) EBL model, and a redshift of the source $z^* = 0.36$ (black, filled circles) and $z_{rec} = 0.2$ (dark grey, filled squares).

$$z_{rec} = \frac{(A - z^*)}{B}, \qquad (1)$$

with A and B given in Prandini et al. (2011). The law was applied to infer the distance of the unknown redshift blazar PKS 1424+240. The value obtained has been confirmed in a study on the host galaxy performed by Meisner (2010).

2.1. The reconstructed *z* of PKS 0447−439

The blazar PKS 0447−439 was observed by the H.E.S.S. IACT observatory between November 2009 to January 2010, for a total of 13.5 hours of data. A clear signal of 13.8 σ of significance was detected at energies above 250 GeV (Zech et al., 2011). The preliminary spectrum extends from 300 GeV up to more than 1 TeV, and is compatible with a steep simple power law of index $\Gamma = 4.36 \pm 0.49$, where the error reported is statistical only. The significant spectral points are drawn in Fig. 1, open markers.

The *Fermi*/LAT spectral slope in the energy range 0.1-100 GeV is $\Gamma_{LAT} = 1.95 \pm 0.03$, as reported in the 1FGL catalogue (Abdo et al., 2010b). We adopted this slope, and not the one extracted from only simultaneous data, to be consistent with the analysis performed for the determination of the $z^* - z_{true}$ law.

The redshift that we obtain when requiring that the deabsorbed PKS 0447−439 spectrum has a slope equal to Γ_{LAT} is $z^* = 0.357 \pm 0.065$, where the error takes into account both the errors on the TeV slope and on the *Fermi*/LAT slope. The corresponding spectrum is drawn in Figure 1, filled black circles. A simple power law fits the data very well, with a probability higher than 99%, and $\chi^2/\mathrm{ndf} = 0.1/3$.

Figure 2 shows the $z^* - z_{true}$ plot in linear scale, adapted from Prandini et al. (2011). The grey markers represent the z^* values of the sixteen sources with known redshifts used to infer the linear relation (dashed-dotted line). The continuous line is the $z^* = z_{true}$ line. All points lie above or on the line, meaning that the values z^* are higher than the real redshifts. This indicates z^* as a good upper limit on the source distance. In our case, we have z^* of 0.357 ± 0.065 and the corresponding upper limit is 0.49 at 2 sigma level. Applying Equation 1 to our data, we obtain for PKS 0447−439 the distance $z_{rec} = 0.20 \pm 0.05$, where

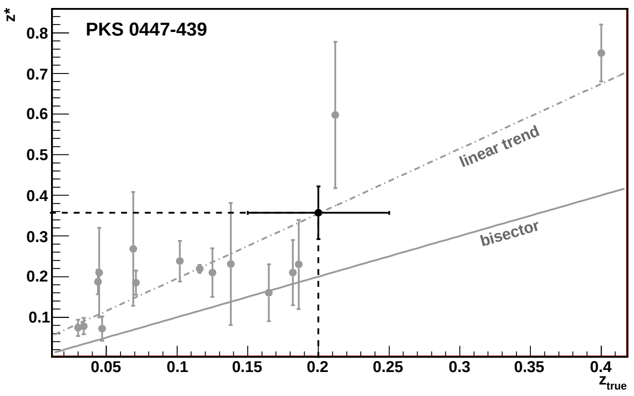

Fig. 2. Diagram adapted from Prandini et al. (2011) representing the linear relation between the redshifts of known distance sources and their z^* values. The value of z^* obtained for PKS 0447−439 in this work is superimposed in black.

the error is statistical only. The differential energy spectrum obtained assuming a distance z of 0.20 is drawn in Figure 1, filled squares. It lies between the observed spectrum (not corrected for EBL absorption) and the spectrum obtained assuming a distance z^*. A simple power law of index $\Gamma = 3.2 \pm 0.5$ fits the data very well (probability > 99%).

The estimated distance obtained perfectly agrees with the value $z = 0.205$ reported by Perlman et al. (1998), and also confirms the lower limit of $z > 0.176$ based on photometric estimates. Therefore, our study strongly supports the value of $z = 0.205$ for PKS 0447−439.

3. Spectral energy distribution

The single-epoch multiwavelength SED of PKS 0447−439 is plotted in Fig. 3, and includes, in addition to the H.E.S.S. data presented in previous section, *Swift*/UVOT, *Swift*/XRT, and *Fermi*/LAT data acquired during the epoch of the H.E.S.S. detection, and other historical data.

Swift observed PKS 0447−439 for about one week at the end of the H.E.S.S. campaign (Zech et al., 2011). Data from the UVOT (Roming et al., 2005) observation taken on December 25 (obs. ID 00038100009) were analysed by means of the `uvotimsum` and `uvotsource` tasks with a source region of 5″, while the background was extracted from a concentric source–free annular region with inner and outer radii of 10″ and 15″, respectively. The extracted magnitudes were corrected for Galactic extinction using the values of Schlegel et al. (1998) and applying the formulae by Pei (1992) for the UV filters, and eventually were converted into fluxes following Poole et al. (2008).

XRT (Burrows et al., 2005) νF_ν points corresponding to the observation of Dec 25 (MJD 55190, obs. ID 00038100010) were obtained through the ASI/ASDC on-line analysis tool[2] (Stratta et al., 2010). The X–ray fluxes were obtained assuming a power law spectrum (best-fit photon index $\Gamma = -2.46$) and fixing the absorption to the Galactic value $N_{\mathrm{H}}^{Gal} = 1.24 \times 10^{20}$ cm^{-2} (after Kalberla et al., 2005).

We retrieved the publicly available data taken by the LAT γ-ray telescope on board the *Fermi* satellite (Atwood et al., 2009) in scanning mode from the NASA database[3]. We selected the good quality ("DIFFUSE" class) events observed within 10° from the source position, taken between MJD 55170 and MJD 55190, and with measured energy in the 0.2–100 GeV interval. We excluded events observed at zenith distances greater than 105° to avoid contamination from the Earth albedo. We performed the analysis by means of the standard science tools, v. 9.18.6, including Galactic and isotropic extragalactic backgrounds and the P6 V3 DIFFUSE instrumental response function. We applied an unbinned likelihood algorithm (`gtlike`) to the data, modelling the source spectrum with a power law model, with the integral flux in the 0.2–100 GeV energy band and photon index left as free parameters. We clearly detected the source with a test statistics (Mattox et al., 1996) TS = 154, and determined $F_{0.2-100\mathrm{GeV}} = 6.93 \pm 1.26 \times 10^{-8}$ ph cm^{-2}s^{-1} and $\Gamma = 1.93 \pm 0.14$.

We also performed the same analysis on the dataset split into logarithmically equal bins of energy, accepting spectral points with TS > 25 and more than three events attributed to the source in the model. The results are plotted in Figure 3.

PKS 0447-439 belongs to the group of highly peaked BL Lac objects. Within the framework of leptonic models, the emission of this type of sources is generally modelled with the one-zone SSC model (e.g. Tavecchio et al., 1998, 2010; Abdo et al., 2011). The idea that the emission mainly originates in a single, uniform, region is supported by the correlated variability observed at different frequencies, especially X-rays and gamma-rays (e.g. Fossati et al., 1998).

The good spectral coverage allows one to firmly constrain the low-energy bump, which is related to synchrotron radiation produced by accelerated electrons in the jet, whose peak lies around 10^{16} Hz (see Fig. 3). LAT and H.E.S.S. data track the so-called SSC component quite well, which shows a broad peak in the GeV region. As detailed in Tavecchio et al. (1998), in the framework of the one-zone SSC model knowing of the peak frequencies and luminosities, together with an estimate of the variability timescale, allows one to determine the physical parameters of the emitting region. An indication of the variability timescale can be derived from the multi-frequency observations, especially those at X-ray energies, which reveal variability on timescale of ≈ days. We therefore assume an upper limit of $t_{\mathrm{var}} < 1$ day for the variability timescale.

We modelled the SED with the one-zone leptonic model described in Maraschi & Tavecchio (2003). The emission region is spherical with radius R, in motion with bulk Lorentz factor Γ at an angle θ with respect to the line of sight. Special relativistic effects are fully accounted for by the relativistic Doppler factor, $\delta = [\Gamma(1 - \beta\cos\theta)]^{-1}$. The energy distribution of the emitting electrons is assumed to be well described by a smoothly connected broken power law function, with minimum, maximum and break Lorentz factor γ_{min}, γ_{max} and γ_{b}, respectively. The SSC emission is calculated assuming the full Klein-Nishina cross section (Jones, 1968). We recall that within the framework of the one-zone SSC model the synchrotron self-absorption causes the source to be opaque below frequencies of about $10^{11} - 10^{12}$ Hz. The emission below these frequencies is therefore produced by more distant, transparent regions of the jet.

Two possible SEDs are reported in Fig. 3, while the corresponding input parameters are listed in Table 1. In the table we also report the derived powers carried by the different components, relativistic electrons, magnetic field and protons (assuming a composition of one cold proton per relativistic electron) and the total radiative power of the jet, $P_{\mathrm{r}} \simeq L_{\mathrm{obs}}/\delta^2$ (in which we assumed $\delta \sim \Gamma$).

[2] http://tools.asdc.asi.it/
[3] http://fermi.gsfc.nasa.gov/

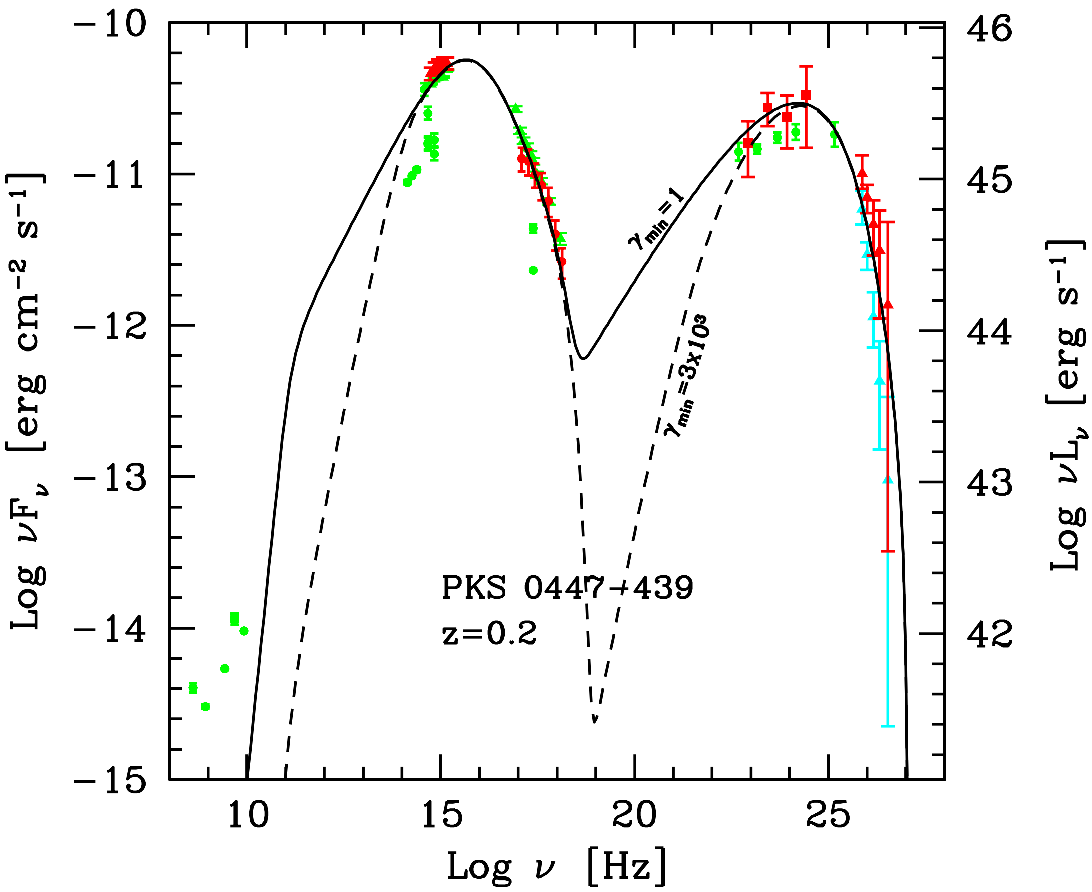

Fig. 3. SED of PKS 0447−439 during the epoch of H.E.S.S. observation (November 2009 – January 2010). Red points represent *Swift*/UVOT, *Swift*/XRT, *Fermi*/LAT and de-absorbed (assuming $z = 0.2$) H.E.S.S. data. Cyan data are the observed H.E.S.S. data. Green symbols report historical data obtained through the ASI/ASDC tools. Green LAT points are from the 1LAC catalogue. The black lines are the result of the one-zone emission leptonic model discussed in the text for two different values of the minimum Lorentz factor of the emitting electrons, $\gamma_{\rm min} = 1$ (solid) and $\gamma_{\rm min} = 3\times10^3$ (dashed). See text for details.

$\gamma_{\rm min}$	$\gamma_{\rm b}$ [10^4]	$\gamma_{\rm max}$ [10^5]	n_1	n_2	B [G]	K [10^3 cm^{-3}]	R [10^{16} cm]	δ	$P_{\rm e}$ [10^{45} erg/s]	P_B [10^{45} erg/s]	$P_{\rm p}$ [10^{45} erg/s]	$P_{\rm r}$ [10^{43} erg/s]
1	2.6	3	2.0	4.4	0.07	5	1.45	39	1.7	7.8×10^{-3}	230	3.8
10^3	2.6	3	2.0	4.4	0.07	5	1.45	39	0.52	7.8×10^{-3}	0.07	3.6

Table 1. Input model parameters for the models reported in Fig. 3. We report the minimum, break and maximum Lorentz factor and the low- and high-energy slope of the electron energy distribution, the magnetic field intensity, the electron density, the radius of the emitting region and its Doppler factor. We also report the derived power carried by electrons, magnetic field, protons (assuming one cold proton per emitting relativistic electron) and the total radiative luminosity.

The jet power is strongly dependent on the total density of particles in the jet that, in turn, is dominated by the number of relativistic electrons at $\gamma_{\rm min}$. While this parameter can be relatively well determined for FSRQs, because the low-energy end of the electron energy distribution is directly accessible through the inverse Compton emission that falls in the X-ray band (e.g. Ghisellini et al., 2010), for BL Lac objects emitting through SSC the constraints are quite loose. As an example of the impact of different values of $\gamma_{\rm min}$ on the derived SED, we report in Fig. 3 two curves, corresponding to $\gamma_{\rm min} = 1$ (solid line) and $\gamma_{\rm min} = 3\times10^3$ (dashed). The two curves clearly show that the value of $\gamma_{\rm min}$ mainly affects the low-energy branch of the synchrotron and SSC bumps. Clearly, any value between 1 and 10^3 is allowed by the available data, which determines a large uncertainty on the inferred powers (see Table 1).

The magnetic field energy density appears to be several orders of magnitude below the equipartition value with the electron energy density and, consequently, the corresponding Poynting flux is negligible compared to the power carried by protons and electrons. This is a feature that PKS 0447−439 shares

with several other TeV BL Lacs (e.g. Tavecchio et al., 2010; Ghisellini et al., 2010).

4. Conclusions

We have presented the results of our study on the distance to PKS 0447−439. This work was triggered by the preliminary measurement of the differential energy spectrum emitted by the source at VHE gamma-rays performed by the H.E.S.S. Collaboration (Zech et al., 2011). The redshift we found with our method, based on both HE and VHE spectra, perfectly agrees with the measurement performed by Perlman et al. (1998), which reports a redshift of 0.205. But it contradicts with the recent assertion of Landt (2012), who claimed a redshift higher than 1.246.

Assuming this redshift, we have built a broadband SED including quasi-simultaneous ultraviolet, X-ray and gamma-ray data acquired during the epoch of the H.E.S.S. detection. The SED can be well fitted within the framework of a homogeneous, leptonic SSC model. The available data leave a large uncertainty on one of the parameters of the model, $\gamma_{\rm min}$, the minimum Lorentz factor of the emitting electrons. This uncertainty propagates to the inferred powers. In any case, the physical parameters that we found suggest a strongly matter-dominated jet, in agreement with the other sources observed at these extreme energies.

The method used in this paper has great potential. A large part of GeV emitting blazars, indeed, about 60% of the BL Lac objects present in the second catalogue of AGN detected by *Fermi*/LAT (Ackermann et al., 2012), has unknown redshift. If detected in the VHE band, the redshift of these powerful objects could be investigated through this technique. Therefore, we encourage the observation of promising TeV emitters among the unknown/uncertain redshift *Fermi* blazars.

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